Spectroscopy of Heavy Quarkonia *

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In the last few years, the CLEO III experiment has recorded a large collection of data sets at the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\psi(2S)$ resonances. Preliminary results of studies of these data sets are shown here, which include the observation of a new $\Upsilon(1D)$ state, as well as several hadronic and radiative transitions of Υ and $\psi(2S)$ states. In addition, precision branching ratio measurements of charmonium and bottomonium states and recent developments involving the $\eta_c(2S)$ and $X(3872)$ states are presented.

1. INTRODUCTION

Heavy quarkonia - $c\bar{c}$ and $b\bar{b}$ bound states - are still a very rich exploration ground. For example, no $b\bar{b}$ singlet states have yet been found, and only a few hadronic and radiative decays are known.

The masses of charm and bottom quarks are relatively large (≈1.5 and ≈4.5 GeV). As a consequence, the velocities of these quarks in hadrons are non-relativistic and the strong coupling constant α_s is quite small (≈0.3 for $c\bar{c}$ and ≈0.2 for $b\bar{b}$). Hence, heavy quarkonia provide the best means of testing the theories of strong interaction, i.e. QCD in both pertubative and non-pertubative regimes, QCD inspired purely phenomenological potential models, NRQCD and lattice QCD.

In this paper, the latest results on charmonium and bottomonium spectroscopy from the CLEO III experiment are presented and recent developments of the searches for the $\eta_c(2S)$ and $X(3872)$ are discussed.

2. THE CLEO III EXPERIMENT AND DATA SETS

The data used in the presented studies were taken with the CLEO III detector at the CESR e^+e^- storage ring. The detector includes a silicon microvertex detector, a drift chamber and a ring imaging cerenkov detector (RICH), as well as a crystal calorimeter. On the outside, the detector is surrounded by muon chambers. The tracking volume is placed in a uniform 1.5 T solenoidal magnetic field.

During the last two years, the CLEO III experiment recorded data at the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ and $\psi(2S)$ resonances, resulting in approximately 38 million hadronic events. In addition, data were also recorded below the peak of each resonance for background purposes and for scans across the resonances. Table 1 summarizes the data sets used.

3. BOTTOMONIUM SPECTROSCOPY

3.1. First Observation of $\Upsilon(1^3D_2)$ State

CLEO has made the first observation of the bottomonium state $\Upsilon(1^3D_2)$ [1]. This state was produced in a two-photon cascade via the $\chi(2P)$ state starting from the $\Upsilon(3S)$ resonance: $\Upsilon(3S) \rightarrow \gamma\chi(2P) \rightarrow \gamma\gamma\Upsilon(1^3D_2)$

To suppress photon backgrounds from π^0s, which are copiously produced in gluonic annihilation of the $b\bar{b}$ states, events with two or more subsequent photon transitions were selected via the cascade $\Upsilon(1^3D_2) \rightarrow \gamma\chi(1P) \rightarrow \gamma\gamma\Upsilon(1S)$ followed by the $\Upsilon(1S)$ annihilation into either e^+e^- or $\mu^+\mu^-$.

In this four-photon cascade 34.5 ± 6.4 signal events were observed which translate into a significance of 10.2σ. The $\Upsilon(1^3D_2)$ mass was measured to $M = 10161.1 \pm 0.6(stat) \pm 1.6(syst)\, MeV$ and the product branching ratio was determined

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Table 1
Summary of the CLEO III data sets used in the studies which are presented in this paper. For comparison, in brackets the number of events recorded with the CLEO II detector are shown.

E_{cm} (GeV)	Resonance	# Events (10^6)	Experiment
9.46	$\Upsilon(1S)$	20 (2)	CLEO III (CLEO II)
10.02	$\Upsilon(2S)$	10 (0.5)	CLEO III (CLEO II)
10.36	$\Upsilon(3S)$	5 (0.5)	CLEO III (CLEO II)
3.69	$\psi(2S)$	3	CLEO III

to $\mathcal{B}(4\gamma\ell^+\ell^-) = 2.6 \pm 0.5(stat) \pm 0.5(syst) \times 10^{-5}$

The measured mass is in good agreement with the mass of the $\Upsilon(1^3D_2)$ state predicted by lattice QCD calculations [2] and those potential models which give a good fit to the other known $b\bar{b}$ states [3]. Also, a prediction of the product branching ratio of 3.76×10^{-5} by Godfrey and Rosner [4] is in good agreement with our branching ratio measurement.

3.2. Measurement of the Muonic Branching Ratio of $\mathcal{B}(\Upsilon(nS)$ Resonances

Previous measurements have established $\mathcal{B}_{\mu\mu}$ with a 2.4% accuracy for the $\Upsilon(1S)$ [5], and a modest 16% accuracy for the $\Upsilon(2S)$ [6,7,8,9] and $\Upsilon(3S)$ [8,10,11]. CLEO has made new measurements of $\mathcal{B}_{\mu\mu}$ in all three resonances using a much larger data set together with a more advanced detector.

To determine $\mathcal{B}_{\mu\mu}$, we measured $\bar{\mathcal{B}} \equiv \Gamma_{\mu\mu}/\Gamma_{had}$, where $\Gamma_{\mu\mu}$ (Γ_{had}) is the rate for Υ decay to $\mu^+\mu^-$ (hadron). Γ_{had} includes all decay modes other than the electromagnetic decays to e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$. Assuming lepton universality, we have $\mathcal{B}_{\mu\mu} = \Gamma_{\mu\mu}/\Gamma = \bar{\mathcal{B}}_{\mu\mu}/(1 + 3\bar{\mathcal{B}}_{\mu\mu})$.

The results of the measurements are shown in Table 2. The measurement for $\Upsilon(1S)$ is in good agreement with the world average. The obtained branching ratios for the $\Upsilon(2S)$ and $\Upsilon(3S)$ resonances are significantly larger than prior measurements and the world average values, resulting in a narrower total decay widths.

3.3. J/ψ Production in $\Upsilon(1S)$ Decays

In Υ decays charm should be produced through the color octet mechanism [12]. To study this mechanism, CLEO searched for the inclusive production of the J/ψ in $\Upsilon(1S)$ resonance decays with J/ψ decaying into e^+e^- and $\mu^+\mu^-$. Additional cuts were used to suppress radiative returns to the J/ψ and $\psi(2S)$. As a cross check, the same analysis method was used on $\Upsilon(4S)$ data to verify that its results were as expected. The branching ratios for the two lepton modes are averaged, thereby obtaining a preliminary branching ratio of $\mathcal{B}(\Upsilon(1S) \rightarrow J/\psi + X) = 6.4 \pm 0.4(stat) \pm 0.6(syst) \times 10^{-4}$.

Also of interest is the beam energy scaled momentum spectrum of the J/ψ's in this process. It appears that this spectrum is softer than what is expected from a naive color octet model, although it might be possible to address this issue with the emission of soft gluons in the theoretical calculations.

3.4. Di-Pion Transitions from $\Upsilon(3S)$

CLEO also performed studies of charged and neutral di-pion transitions from the $\Upsilon(3S)$ resonance to $\Upsilon(2S)$ and $\Upsilon(1S)$. For the neutral dipion transitions of $\Upsilon(3S)$ to $\Upsilon(2S)$ and $\Upsilon(1S)$ we measure the preliminary branching ratios as

$$\mathcal{B}(\Upsilon(3S) \rightarrow \pi^0\pi^0\ \Upsilon(2S)) = 2.02 \pm 0.18(stat) \pm 0.38(syst)\%$$

$$\mathcal{B}(\Upsilon(3S) \rightarrow \pi^0\pi^0\ \Upsilon(1S)) = 1.88 \pm 0.08(stat) \pm 0.31(syst)\%$$

The $\pi^0\pi^0$ effective mass spectrum for the transition to the $\Upsilon(2S)$ has a shape consistent with several theoretical predictions. The mass spectrum for the transition to the $\Upsilon(1S)$ has a "double humped" shape which was also observed in charged di-pion transitions [13]. Further measurements of neutral and the charged di-pion transitions are in progress.

3.5. Radiative Transitions from $\Upsilon(nS)$

Radiative transitions from $\Upsilon(nS)$ states are an

Table 2
Summary of the branching ratio measurements of $\mathcal{B}(\Upsilon(nS) \to \mu^+\mu^-)$. For comparison, the world averages (PDG) [5] are given.

$\mathcal{B}_{\mu\mu}$ (%)	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
CLEO	$2.53 \pm 0.02 \pm 0.05$	$2.11 \pm 0.03 \pm 0.05$	$2.44 \pm 0.07 \pm 0.05$
PDG	2.48 ± 0.06	1.31 ± 0.21	1.81 ± 0.17

excellent place to look for new intermediate resonances, such as $b\bar{b}$ singlet states.

In M1 transitions, CLEO has searched for the states $\eta_b(1S)$ and $\eta_b(2S)$. No significant signals were found and only upper limits for branching ratios as a function of the photon energy were determined.

In E1 transitions, we observed the following three transitions:
$\Upsilon(3^3S_1) \to \gamma\ \chi_b(1^3P_J)$
$\chi_b(1^3P_0) \to \gamma\ \Upsilon(1^3S_1)$
$\chi_b(2^3P_0) \to \gamma\ \Upsilon(2^3S_1)$

No preliminary branching ratios are available at this time. Further precision measurements are in progress.

4. CHARMONIUM SPECTROSCOPY

4.1. Radiative Transitions from $\psi(2S)$

CLEO has measured the branching ratios for the radiative transitions $\psi(2S) \to \gamma\chi_c(1P_J)$ and $\psi(2S) \to \gamma\eta_c(1S)$. Table 3 summarizes the four measurements. The ratios are in good agreement with the Particle Data Group (PDG) averages. CLEO also confirms the M1 transition to $\eta_c(1S)$ made by Crystal Ball. However, we find no indication of the M1 transition to $\eta_c(2S)$ which was reported by the Crystal Ball collaboration 20 years ago.

4.2. Experimental Results on $\eta_c(2S)$

The η_c' has a very colorful history with one observation followed by a number of fruitless searches. This situation changed recently with the Belle observation of robust η_c' signals in the two channels $B^\pm \to K^\pm\eta_c' \to K^\pm K_s K^\pm\pi^\mp$ with $M = 3654 \pm 6(stat) \pm 8(syst)\ MeV$ and $e^+e^- \to J/\psi\eta_c$ with $M = 3622 \pm 12\ MeV$ [14,15], quickly followed by BaBar and CLEO observations of η_c' signals in two-photon fusion processes. BaBar reported a mass of $M = 3630.8 \pm 3.4(stat) \pm 1.0(syst)\ MeV$ and a width of $\Gamma = 17.0 \pm 8.3(stat) \pm 2.5(syst)\ MeV$ [16]. CLEO measured the mass to $M = 3642.9 \pm 3.1(stat) \pm 1.5(syst)\ MeV$ and the width to $\Gamma < 31 MeV$ (90% C.L.) [17]. The CLEO observation was made in two data sets with substantially different detectors and software systems. The results of the three experiments are in reasonable agreement.

Using a combined mass value (Belle, BaBar, CLEO) of $M = 3637 \pm 4.4\ MeV$, the value of the hyperfine mass splitting between the $\psi(2S)$ and the η_c' can be given as $\Delta M(2S) = 48.6 \pm 4.4\ MeV$. This value for $\Delta M(2S)$ is much smaller than most theoretical predictions and should lead to a new insight into coupled channel effects and spin-spin contribution of the confinement part of the $q\bar{q}$ potential.

4.3. Search for the Narrow State $X(3872)$

This new narrow state was first observed by the Belle collaboration in the decay channel $B^\pm \to K^\pm\ X(3872)$ with $X(3872) \to \pi^+\pi^- J/\psi$ and J/ψ decaying into a lepton pair [18]. The reported mass and width are $M = 3872.0 \pm 0.6(stat) \pm 0.5(syst)\ MeV$ and $\Gamma < 2.3\ MeV$ (90% C.L.). The CDF and D0 collaborations have confirmed the $X(3872)$ observation in proton-antiproton annihilation $p\bar{p} \to X(3872) + X$ with $X(3872) \to \pi^+\pi^- J/\psi$ and J/ψ decaying into a muon pair [19,20]. The reported masses are $M = 3871.3 \pm 0.7(stat) \pm 0.4(syst)\ MeV$ (CDF) and $M = 3871.8 \pm 3.1(stat) \pm 3.0(syst)\ MeV$ (D0).

CLEO searched for the $X(3872)$ state in untagged two-photon fusion processes and initial-state-radiation production, analyzing the exclusive channels $X(3872) \to \pi^+\pi^- J/\psi$ with J/ψ decaying into a lepton pair. No signal was found,

Table 3
Summary of the branching ratio measurements for $\psi(2S)$ radiative transitions. For comparison, the PDG values [5] are given.

$\mathcal{B}$ (%)	$\psi(2S) \to \gamma\chi_c(1P_J)$			$\psi(2S) \to \gamma\eta_c(1S)$
	J = 2 (E1 line)	J = 1 (E1 line)	J = 0 (E1 line)	J = 0 (M1 line)
CLEO	9.75 ± 0.14 ± 1.17	9.64 ± 0.11 ± 0.69	9.83 ± 0.13 ± 0.87	0.278 ± 0.033 ± 0.049
PDG	7.8 ± 0.8	8.7 ± 0.8	9.3 ± 0.8	0.28 ± 0.06

but upper limits could be set. For untagged two-photon fusion processes, we find $(2J+1)\Gamma_{\ell\ell}\mathcal{B}(X \to \pi^+\pi^- J/\psi) < 16.7\ eV$ (90% C.L.) and for ISR production we report $\Gamma_{ee}\mathcal{B}(X \to \pi^+\pi^- J/\psi) < 6.8\ eV$ (90% C.L.).

5. SUMMARY AND CONCLUSION

CLEO is now fully exploiting the world's largest sample of Υ decays. We have reported on the observation of the $\Upsilon(1^3D_2)$ state and several hadronic and radiative transitions of Υ and $\psi(2S)$ states. We also measured the rate for inclusive ψ production in $\Upsilon(1S)$ decays. In addition, we presented precision branching ratio measurements and searches for $\eta_c(2S)$ and $X(3872)$. All results are preliminary.

As demonstrated above, spectroscopy of heavy quarkonia is a very active field. Collections of large data samples are now available from CLEO III ($b\bar{b}$), BES II ($c\bar{c}$) and CLEO-c ($c\bar{c}$). Many new important experimental observations and measurements have emerged and many more are expected for the near future.

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